DRAFT VERSION FEBRUARY 5, 2008
Preprint typeset using LaTeX style emulateapj v. 6/22/04

THE GALACTIC NATURE OF HIGH VELOCITY CLOUD COMPLEX WB

C. THOM[1,2], M. E. PUTMAN[3], B. K. GIBSON[1,4], N. CHRISTLIEB[5], C. FLYNN[2], T. C. BEERS[6], R. WILHELM[7] AND Y.S. LEE[6]

Draft version February 5, 2008

ABSTRACT

We have detected absorption lines from the High Velocity Cloud Complex WB in the spectrum of the star HE 1048+0231. This detection sets an upper distance limit to the cloud of $8.8^{+2.3}_{-1.3}$ kpc. Non-detection (at $> 4\sigma$ confidence) in the star HE 1138−1303 at 7.7 ± 0.2 kpc sets a probable lower limit. The equivalent width of the Ca II K line due to the HVC (W_λ(Ca II K) = 114.6 ± 4.4 mÅ) corresponds to a column density of N(Ca II) = $1.32 \pm 0.05 \times 10^{12}$ cm^{-2}. Using an H I spectrum from the Leiden/Argentine/Bonn survey, we calculated N(Ca II)/N(H I) = $81 \pm 16 \times 10^{-9}$. These distance limits imply an H I mass limit of $3.8 \times 10^5 M_\odot < M_{\rm H\,I} < 4.9 \times 10^5 M_\odot$. The upper distance limit imposed by these observations shows that this HVC complex has a probable Galactic or circum-Galactic origin. Future metallicity measurements will be able to confirm or refute this interpretation.

Subject headings: Galaxy: halo — Galaxy: evolution — ISM: clouds — ISM: individual (Complex WB)

1. INTRODUCTION

High Velocity Clouds (HVCs) are clouds of neutral hydrogen (H I) gas with velocities that are inconsistent with a simple model of differential Galactic rotation. Since a kinematic distance cannot be derived, the exact location and nature of the HVCs has been the topic of much speculation. Determination of the distances to HVCs is vitally important, as such measurements can constrain their likely origins, and establish their physical parameters, many of which scale with distance.

The HVCs have been ascribed to many different origins, from local Galactic processes, to distant proto-galaxies. Shapiro & Field (1976) were the first to suggest the existence of a Galactic Fountain, in which supernovae drive hot gas into the halo, which then condenses and returns to the disk (e.g. Bregman 1980). Extra-Galactic origins have been discussed almost since the discovery of HVCs (Oort 1966). Blitz et al. (1999) have inspired vigorous debate by reviving and further refining this scenario, noting that it naturally explains the kinematics of clouds towards the bary- and anti-barycenter of the Local Group. They suggested that these distant HVCs could be dark-matter dominated objects, which some have claimed might be the solution to the "satellite problem" of Cold Dark Matter simulations (namely, that many more dark matter haloes are predicted to exist than satellite galaxies observed, e.g. Klypin et al. 1999).

Despite many years of effort, few HVCs have been detected in absorption against stellar probes. Of the traditional complexes, only M and A have been detected (Danly et al. 1993; van Woerden et al. 1999). Several other smaller clouds have also been detected in the spectra of background stars (e.g. Bates et al. 1990; Sembach et al. 1991). Wakker (2001) provides a much more comprehensive summary.

Wannier et al. (1972) were the first to report on the positive velocity clouds in the third and fourth Galactic quadrants. Fainter than the traditional negative velocity complexes such as A and C, they were divided into four separate complexes WA – WD (Wakker & van Woerden 1991, hereafter WvW91). These complexes span a wide range of position and velocity space, comprising a total of 64 clouds in the WvW91 catalog, with mostly moderate deviation velocities[8]. Complex WB ($l = 225-265°$; $b = 0-60°$) is composed of 29 separate clouds, with a total H I mass M(H I) = $0.236\, d^2(\mathrm{kpc})\, S(\mathrm{Jy\,km\,s^{-1}}) \sim 6.5 \times 10^3\, d^2\, M_\odot$, where S is the integrated flux and d is the distance. Robertson et al. (1991) have observed the Wannier Clouds in absorption towards the Seyfert galaxy PKS 0837–12. Along this line of sight they derive a N(Ca II)/N(H I) ratio of 160×10^{-9}. Using a higher resolution H I spectrum, Wakker (2001) revised this value upwards to 280×10^{-9}. Both sets of authors note the anomalously high calcium abundance (one of the highest measured for any HVC), while Robertson et al. concluded that a distance is necessary to discern between the various possible explanations they offered.

The Wannier clouds, along with the extreme positive velocity clouds (population EP) lie in the direction of the Local Group anti-barycenter. They are explicitly included in the Blitz et al. (1999) scenario as being very distant and undergoing infall towards the Local Group barycenter. Thus a confirmed upper limit on the distance would stand in opposition to this suggestion and may have broader consequences for the HVCs as a whole.

2. OBSERVATIONS AND DATA

As part of a program to bracket the distances to many HVCs, we have obtained echelle spectra of two stars: HE 1048+0231 (which is aligned with WW 35) and HE 1138−1303 (WW 62). Both stars were drawn from our catalog of Field Horizontal Branch stars aligned with HVC gas (Thom et al. 2005); Figure 1 shows their alignment with the HVC gas. Basic information for both lines of sight is listed in Table 1. Results for other targets in this program will be re-

Electronic address: cthom@astro.swin.edu.au
[1] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, Victoria, 3122, Australia
[2] Tuorla Observatory, Väisäläntie 20, FI-21500, Piikkiö, Finland
[3] Dept. of Astronomy, University of Michigan, 500 Church St., Ann Arbor, MI 48109
[4] Centre for Astrophysics, University of Central Lancashire, Preston, PR1 2HE, UK
[5] Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg,Germany
[6] Department of Physics & Astronomy, and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, E. Lansing, MI, 48824
[7] Department of Physics, Texas Tech University, Lubbock, TX 79409

[8] Deviation velocity is the amount by which a velocity deviates from allowed Galactic rotation velocities (Wakker 1991).

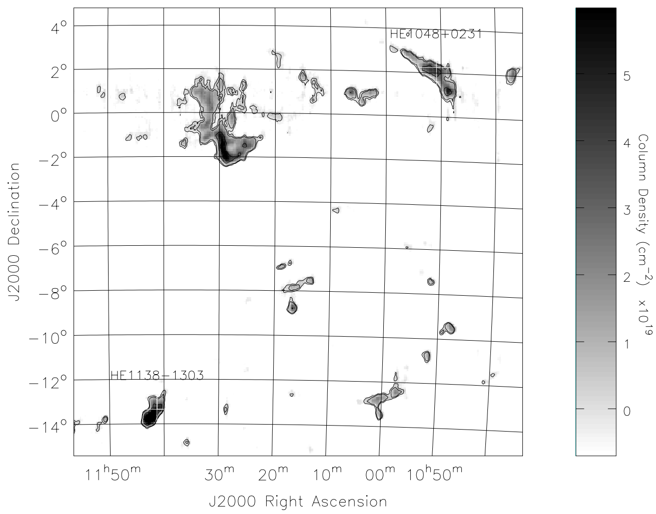

FIG. 1.— HIPASS column density map showing region around both sight lines (not the whole of Complex WB). The labelled white plus signs indicate the positions of the stars. Contours are drawn at $8.0 \times 10^{18}, 1.0 \times 10^{19}$, 2.0×10^{19} and 3.0×10^{19} cm^{-2}.

TABLE 1
BASIC PARAMETERS OF HVC PROBES.

	HE 1048+0231	HE 1138−1303
Stellar Properties		
RA,DEC (J2000)	10:50:52.5 +02:15:19	11:41:14.8 −13:20:17
(l,b)	(248.517, +51.911)	(277.905, +46.098)
Magnitude (V_0, $(B-V)_0$)	16.51 ± 0.03; 0.00	14.87 ± 0.01; 0.40
Distance (kpc)	$8.8^{+2.3}_{-1.3}$	7.7 ± 0.2
Exp time (s)	10×1800	3×1800
Signal-to-noise (pix^{-1})	60	90
HVC properties		
N(H I) ($\times 10^{19}$ cm^{-2})	1.64 ± 0.31	1.73 ± 0.33
$v_{\rm LSR}$(km s^{-1})	96	110
W_λ (Ca II K)(mÅ)	116.2 ± 4.6	$\sigma(W_\lambda) = 3.4$
W_λ (Ca II K)(mÅ)	112.9 ± 4.1	$\sigma(W_\lambda) = 3.9$
W_λ (Ca II H)(mÅ)	69.5 ± 7.2	$\sigma(W_\lambda) = 3.3$
W_λ (Na I D)(mÅ)	31.0 ± 7.0	$\sigma(W_\lambda) = 4.4$
W_λ (Na I D_2)(mÅ)	51.3 ± 7.7	$\sigma(W_\lambda) = 5.0$

NOTE. — Magnitudes have been corrected for dust extinction using the maps of Schlegel et al. (1998). Distance errors are computed based on the variation of atmospheric parameters (obtained from photometric errors).

ported in a future paper.

The stars HE 1048+0231 and HE 1138−1303 were observed in excellent conditions on 2005 April 01 and 2005 March 31 respectively, using the MIKE spectrograph (Bernstein et al. 2003) mounted on the Magellan Clay 6.5m telescope. Spectra covering the range 3350 – 9500 Å with resolving power (as measured from arc lines) R = 40,000 at 4000 Å and R = 31,000 at 5900 Å were obtained. The data were reduced using the MIKE *redux* package[9] and corrected from a heliocentric to Local Standard of Rest (LSR) frame for comparison with H I emission data.

H I emission data were obtained from two sources. First we used the H I spectra presented in Thom et al. (2005), which was taken from the H I Parkes All-Sky Survey. These data were reduced in such a way as to be sensitive to extended emission (Putman et al. 2003). Secondly, to estimate the column density along the line of sight, we obtained higher velocity resolution (but poorer spatial resolution) data from the Leiden/Argentine/Bonn (LAB) survey (Kalberla et al. 2005).

Accurate *UBV* photometry was obtained with the WIYN 0.9 m telescope between 2005 November 20 – 22, with Landolt standards obtained at the same time. The data were reduced in the usual fashion using *IRAF* and aperture photometry was performed. The results are listed in Table 1.

3. RESULTS

3.1. HE1048+0231

In the spectrum of HE 1048+0231 we detect a clear signature of absorption, shown in Figure 2 (left panel). We plot the optical absorption and H I emission spectra aligned in velocity space. Both lines of the Na I doublet, the Ca II H and K lines, and the HIPASS and LAB H I spectra are shown. Note that two separate Ca II K spectra are shown, since this line falls onto two adjacent echelle orders, allowing us to confirm in one order what is seen in the other. Significant HVC absorption ($> 3\sigma$) was detected in all of these lines. Since the same absorption structure is seen at the same velocity of several different species, we can reject the possibility that these are intrinsic stellar features. The shaded region indicates the boundary of lower velocities ($|v_{\rm LSR}| \leq 90\,{\rm km\,s^{-1}}$) where HIPASS data are unreliable, while the vertical line shows the HVC velocity ($|v_{\rm LSR}| = 96\,{\rm km\,s^{-1}}$).

Equivalent widths (EWs) and errors were derived following the method outlined in Sembach & Savage (1992, hereafter SS92). Legendre polynomials (order 2 – 5) were fit to the local continuum regions ($|v_{\rm LSR}| < 1000\,{\rm km\,s^{-1}}$), with an F-test determining the appropriate polynomial order. EWs were measured by direct integration of the normalized spectra in the range $78-115\,{\rm km\,s^{-1}}$, as determined from the Ca II K absorption. EW errors due to both intensity variations and continuum placement were added in quadrature. The results are listed in Table 1. Note that the EWs of the Ca II K and Ca II H are in the expected $\sim 2:1$ ratio (at the limit of the range permitted by the errors), as is the EW ratio of Na I D_2 to Na I D_1.

In order to disentangle the complex absorption structure, multiple Gaussians were fit to the HVC absorption features. Averaging over the 5 separate spectral regions, we determined line centers of 91.5 and $105.2\,{\rm km\,s^{-1}}$. A multi-component Gaussian decomposition was attempted for the HVC emission seen in the LAB spectrum, but the data did not support more than a single component, centered at $96\,{\rm km\,s^{-1}}$. We conclude that beam smearing is a significant problem – the H I data have a spatial resolution of 40 arcmin (Kalberla et al. 2005). The HIPASS data, while having higher spatial resolution, have a much coarser velocity sampling, and were no help in this regard. This multiple absorption is indicative of either two distinct, spatially aligned clouds, or two components of the same cloud with a large kinematic separation. Higher resolution data are required to fully disentangle the possibilities.

Averaging over the two Ca II K measurements, we obtained N(Ca II) $= 1.32 \pm 0.05 \times 10^{12}\,{\rm cm^{-2}}$, assuming a linear relation between equivalent width and column density (e.g. Savage & Sembach 1996). The corresponding total H I column density (from the LAB data) is N(H I) $= 1.64 \pm 0.31 \times$

[9] See http://web.mit.edu/∼ burles/www/MIKE/

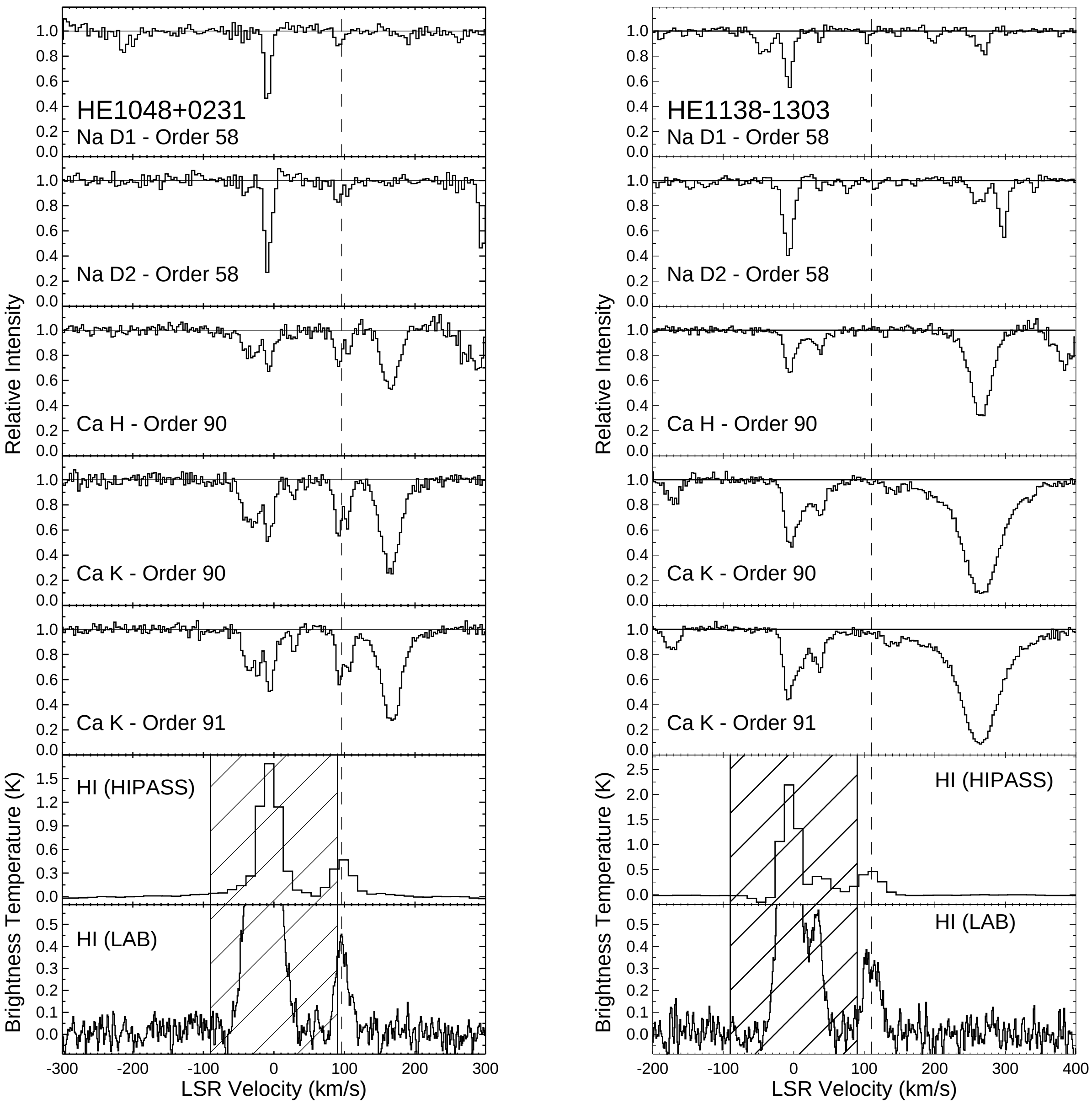

FIG. 2.— Optical and radio spectra along the line of sight towards HE 1048+0231 (left panel) and HE 1138−1303 (right panel). For HE 1048+0231, both Ca II lines, and at least one Na I line, show the same absorption structure. The large absorption line at $\sim 170\,\mathrm{km\,s^{-1}}$ is the intrinsic stellar Ca II line, while the complex absorption near $0\,\mathrm{km\,s^{-1}}$ is due to local gas. For HE 1138−1303, no such HVC absorption is present; the absorption line at $\sim 140\,\mathrm{km\,s^{-1}}$ near Ca II K is an intrinsic Ti II line. The shaded region in the H I spectra show the limit of low velocity gas; below this the HIPASS data are expected to be unreliable. The dashed vertical line is drawn at the velocity of the HVC, as measured in the LAB spectrum (see § 3.1).

$10^{19}\,\mathrm{cm^{-2}}$, where we have again assumed the optically thin case (since the H I brightness temperature is low, this assumption is valid; Dickey & Lockman 1990). Combining these two values yields a Ca II to H I ratio of N(Ca II)/N(H I) = $81 \pm 16 \times 10^{-9}$. The solar Ca II abundance is $A_{\odot} = 2.2 \times 10^{-6}$ (Anders & Grevesse 1989), yielding an abundance of 0.04 solar. Note that ionization effects (which are difficult to estimate) have not been taken into account.

We attempted to confirm the low surface gravity nature of HE 1048+0231 using the method of Wilhelm et al. (1999). We derived stellar parameters in the range T_{eff} = 9350 − 9750 K, $\log g$ = 3.5 − 4.25, with an associated distance d = $8.8^{+2.3}_{-1.3}$ kpc. Note that these values place HE 1048+0231 on the main-sequence, with a color consistent with spectral type A0. The uncertainty in $\log g$ (and hence the distance) is due mainly to the degeneracy of $U-B$ in this temperature range.

3.2. HE1138–1303

The star HE 1138−1303 is aligned with cloud WW 62. While not originally classified as part of Complex WB, its position and velocity strongly suggest an association. Note also that in this region, the complexes WA and WB inhabit similar parts of position and velocity space (c.f. Figs 1j and 1k of WvW91). The interpretation of the optical spectrum of HE 1138−1303 (Fig 2, right panel) is less certain than that of HE 1048+0231. The same methods as described above and in SS92 were applied, with the results given in Table 1. Integration was performed in the range

$92-127\,\mathrm{km\,s^{-1}}$ (± 1.5 the Gaussian σ determined from the LAB spectrum). No significant absorption near Ca II H or K was detected. There is a single-pixel feature at the location of the Na I D_1line which yields an EW of W_λ(Na I D_1) = 9.3 ± 4.4 mÅ. Around Na I D_2 there is an unidentified absorption feature with W_λ(Na I D_2) = 12.1 ± 5.0 mÅ. Neither of these are statistically significant detections, nor are their locations correlated. Together with the lack of Ca II K absorption, we conclude that there is no evidence of HVC absorption towards HE 1138 − 1303.

The interpretation of the lack of observed HVC absorption in the direction of HE 1138-1303 requires some caution (see comments by Wakker 2001). We first assumed that beam-smearing would contribute a factor of two reduction in the H I column density along the sight line. Next, metallicities are known to vary within a cloud (Gibson et al. 2001). We thus assumed N(Ca II)/N(H I) is a factor of two lower than that measured in the HE 1048 + 0231 line of sight (which is unlikely when the PKS 0837–12 sight line is considered; see Robertson et al. 1991) . We allow a further factor of two reduction to allow for ionization uncertainty. Taking this into account, we would then expect to observe a Ca II K EW of ~ 15 mÅ. The measured error in these orders is ~ 3.4 mÅ, giving a ratio of $W_{\lambda,expected}/\sigma(W_\lambda)\sim 4.4$, i.e. we expect to see HVC absorption with at least 4σ confidence (or more, since it is unlikely that all the above factors would be perfectly correlated).

We also performed a stellar parameter analysis for HE 1138 − 1303. The results suggested stellar parameters $T_{\rm eff}$ = 6000 K, $\log g$ = 2.0 (i.e. on the Horizontal Branch), at a distance of $\sim 7.7\pm 0.2$ kpc. These parameters are near the limits of the models, so the errors are likely to be somewhat underestimated.

4. DISCUSSION

The upper distance limit we obtain places WB firmly inside the halo of the Milky Way. The non-detection towards HE 1138 − 1303 sets a probable lower limit. Although a scenario in which the two clouds are physically disjoint is not excluded, it is unlikely given the location and kinematics of the gas. A distance of 7.7 kpc < d < 8.8 kpc implies a total H I mass of $3.8\times 10^5\,M_\odot < M_{\rm H\,I} < 4.9\times 10^5\,M_\odot$ for the entire complex. We measured a Ca II abundance $N(\mathrm{Ca\,II})/N(\mathrm{H\,I})$ = $81\pm 16\times 10^{-9}\,\mathrm{cm^{-2}}$ (~ 0.04 solar) which is about a factor of four less than that seen towards PKS 0837–120 (280×10^{-9}; Wakker 2001), $\sim 35^\circ$ away from HE 1048 + 0231.

Since the H I data have poor spatial resolution (in the case of the LAB) and poor velocity resolution (HIPASS), we cannot resolve individual cloud structures; the H I column density estimates are likely to be accurate only to a factor of two. While the broad characteristics of the H I and optical data match, we cannot resolve any condensations within the cloud, which are suggested by the multiple absorption components seen in the optical data. Higher resolution interferometric or large single-dish data (e.g. ALFA at Arecibo), with good velocity resolution, are thus crucial.

In the Galactic rest frame, the measured velocity of Complex WB ($96\,\mathrm{km\,s^{-1}}$) implies that the complex is in-falling with $v_{\rm GSR} = -30\,\mathrm{km\,s^{-1}}$. A maximum distance of 9 kpc places Complex WB 7 kpc above the disk of the Milky Way, some 12 kpc from the Galactic center. Both fountain and infalling gas interpretations are consistent with the data. Under an infall scenario, the anomalously high N(Ca II)/N(H I) measurement might be explained in terms of low depletion due to low dust content or hydrogen ionization (which has not been taken into account here). If the gas is closer to the disk, then Complex WB may be fountain gas returning to the disk. The Ca II abundance is not implausible since Ca II does not accurately trace the total gas metallicity, although a more accurate metallicity estimate would be very helpful for this discussion.

The distance bracket towards Complex WB is an important step towards the final goal of determining the distances to a large sample of High Velocity Clouds. It is one of only a few upper distance limits to HVCs, and the first direct limit towards a cloud that was predicted to be very distant by the Blitz et al. (1999) model. Our results add to the growing body of evidence that the High Velocity Clouds are much more likely to belong to a Galactic or circum-Galactic population, rather than a distant, extra-Galactic one.

We are grateful to Rebecca Bernstein, Ian Thompson and Steve Shectman for help with the MIKE spectrograph. We thank Scott Burles and Jason Prochaska for help with the MIKE redux package. Thanks to Peter Kalberla for providing the LAB survey data before publication. Nathan DeLee participated in the WIYN observations, for which we are grateful. CT would like to thank Tuorla Observatory for its support, and acknowledges travel support from the ANSTO AMRF Programme. The financial support of the Australian Research Council is greatly appreciated. TCB acknowledges partial support NSF grants AST 04-06784 and PHY 02-16783.

REFERENCES

Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bates, B., Catney, M. G., & Keenan, F. P. 1990, MNRAS, 242, 267
Bernstein, R., Shectman, S. A., Gunnels, S. M., Mochnacki, S., & Athey, A. E. 2003, in Proc. SPIE, Vol. 4841, 1694
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
Bregman, J. N. 1980, ApJ, 236, 577
Danly, L., Albert, C. E., & Kuntz, K. D. 1993, ApJ, 416, L29+
Dickey, J. M. & Lockman, F. J. 1990, ARA&A, 28, 215
Gibson, B. K., Giroux, M. L., Penton, S. V., Stocke, J. T., Shull, J. M., & Tumlinson, J. 2001, AJ, 122, 3280
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., & Pöppel, W. G. L. 2005, A&A, 440, 775
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Oort, J. H. 1966, Bull. Astron. Inst. Netherlands, 18, 421
Putman, M. E., Staveley-Smith, L., Freeman, K. C., Gibson, B. K., & Barnes, D. G. 2003, ApJ, 586, 170
Robertson, J. G., Schwarz, U. J., van Woerden, H., Murray, J. D., Morton, D. C., & Hulsbosch, A. N. M. 1991, MNRAS, 248, 508
Savage, B. D. & Sembach, K. R. 1996, ARA&A, 34, 279
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sembach, K. R. & Savage, B. D. 1992, ApJS, 83, 147
Sembach, K. R., Savage, B. D., & Massa, D. 1991, ApJ, 372, 81
Shapiro, P. R. & Field, G. B. 1976, ApJ, 205, 762
Thom, C., Gibson, B. K., & Christlieb, N. 2005, ApJS, 161, 147
van Woerden, H., Schwarz, U. J., Peletier, R. F., Wakker, B. P., & Kalberla, P. M. W. 1999, Nature, 400, 138
Wakker, B. P. 1991, A&A, 250, 499
—. 2001, ApJS, 136, 463
Wakker, B. P. & van Woerden, H. 1991, A&A, 250, 509
Wannier, P., Wrixon, G. T., & Wilson, R. W. 1972, A&A, 18, 224
Wilhelm, R., Beers, T. C., & Gray, R. O. 1999, AJ, 117, 2308